A response to "Likelihood ratio as weight of evidence: A closer look" by Lund and Iyer

Supplementary Material 1

Contents

Key Quotes from Standards, Guidelines and Position Statements

This section presents a selection of key quotes from standards, guidelines and position statements supporting and recommending a likelihood ratio (LR) approach for the evaluation of evidence in forensic science.

NRC II (1996). National Research Council Committee on DNA Forensic Science, The Evaluation of Forensic DNA Evidence, National Academy Press, Washington D.C.

In the section entitled "Mixed Samples":

Mixed samples are sometimes found in crime situations—for instance, blood from two or more persons at the scene of a crime, victim and assailant samples on a vaginal swab, and material from multiple sexual assailants. In many cases, one of the contributors—for example, the victim—is known, and the genetic profile of the unknown is readily inferred. In some cases, it might be possible to distinguish the genetic profiles of the contributors to a mixture from differences in intensities of bands in an RFLP pattern or dots in a dot-blot typing; in either case, the analysis is similar to the unmixed case. However, when the contributors to a mixture are not known or cannot otherwise be distinguished, a likelihood-ratio approach offers a clear advantage and is particularly suitable.

DNA Commission of the International Society for Forensic Genetics (ISFG): Guidelines for mitochondrial DNA typing, 2000. Carracedo, Bär, Lincoln, Mayr, Morling, Olaisen, Schneider, Budowle, Brinkmann, Gill, Holland, Tully, Wilson. Forensic Sci. Int. 110: 79-85; and Bär, Brinkmann, Budowle, Carracedo, Gill, Holland, Lincoln, Mayr, Morling, Olaisen, Schneider, Tully, Wilson, Int. J. Legal Med. 113 (2000) 193-196.

page Forensic Sci. Int. 84 / Int. J. Legal Med. 195:

As for other DNA evidence it is desirable to communicate the value of the mtDNA evidence using likelihood ratios.

DNA Commission of the International Society of Forensic Genetics (ISFG): Recommendations on forensic analysis using Y-chromosome STRs, 2001. Gill, Brenner, Brinkmann, Budowle, Carracedo, Jobling, de Knijff, Kayser, Krawczak, Mayr, Morling, Olaisen, Pascali, Prinz, Roewer, Schneider, Sajantila, Tyler-Smith. Forensic Sci. Int. 124: 5-10; and Gill, Brenner, Brinkmann, Budowle, Carracedo, Jobling, de Knijff, Kayser, Krawczak, Mayr, Morling, Olaisen, Pascali, Prinz, Roewer, Schneider, Sajantila, Tyler-Smith. Int. J. Legal Med. 114 (2001) 305-309.

page Forensic Sci. Int. 8 / Int. J. Legal Med. 307:

There are two ways to report Y-chromosome polymorphisms. Either the counting method may be used (…) or a frequency (or a likelihood ratio) may be used.

Considerations by the European DNA profiling (EDNAP) group on the working practices, nomenclature and interpretation of mitochondrial DNA profiles, 2001. Tully, Bär, Brinkmann, Carracedo, Gill, Morling, Parson, Schneider. Forensic Sci. Int. 124: 83-91.

page 88:

Although the current data regarding mtDNA substitution rates and population genetics are limited, the general likelihood ratio formulation is a useful framework upon which an assessment of evidential significance can be made:

$$\mathrm{LR} = \frac{\text{Probability of obtaining SQ and SK}|\text{Q and K are from the same maternal lineage}}{\text{Probability of obtaining SQ and SK}|\text{Q and K are not from the same maternal lineage}}$$

Examples of how this framework could be used in commonly encountered situations are given below.

where *Q* = evidential material, *K* = known sample, *SQ* = sequence of the evidential material, and *SK* = sequence of the reference sample.

Paternity Testing Commission of the International Society of Forensic Genetics (ISFG): Recommendations on genetic investigations in paternity cases, 2002. Morling, Allen, Carracedo, Geada, Guidet, Hallenberg, Martin, Mayr, Olaisen, Pascali, Schneider. Forensic Sci. Int. 129: 148-157; Morling, Allen, Carracedo, Geada, Guidet, Hallenberg, Martin, Mayr, Olaisen, Pascali, Schneider. Int. J. Legal Med. 117 (2003) 51-61.

page Forensic Sci. Int. 155 / Int. J. Legal med. 59:

ISFG-recommendation: *If the weight of the evidence is calculated, it shall be based on likelihood ratio principles. The Paternity Index (PI) is a likelihood ratio:*

$$PI = \frac{probability\ (types\ observed|the\ hypothesis\ is\ that\ the\ tested\ man\ is\ the\ father)}{probability(types\ observed|the\ hypothesis\ is\ that\ a\ random\ man\ is\ the\ father)}$$

DNA commission of the International Society of Forensic Genetics (ISFG): Recommendations on the interpretation of mixtures, 2006. Gill, Brenner, Buckleton, Carracedo, Krawczak, Mayr, Morling, Prinz, Schneider, Weir. DNA commission of the International Society of Forensic Genetics: Recommendations on the interpretation of mixtures, Forensic Sci. Int. 160: 90-101.

page 91:

The advantage of the LR framework is that stutter and dropout can be assessed probabilistically, and it is the only way to provide a meaningful calculation based on the probability of the evidence under Hp and Hd. The RMNE method has considerable intuitive appeal but usually entails an unrealistically simple model of DNA evidence and is therefore restricted in its use to unambiguous profiles. Even in those cases RMNE has further shortcomings as it does not make full use of the evidence.

A likelihood ratio is therefore preferred. There is a broad consensus view on this point that originates from the original recommendation of the NRC II.

page 92:

Recommendation 1: The likelihood ratio is the preferred approach to mixture interpretation. (…)

and:

<u>Recommendation 2</u>: Even if the legal system does not implicitly appear to support the use of the likelihood ratio, it is recommended that the scientist is trained in the methodology and routinely uses it in case notes, advising the court in the preferred method before reporting the evidence in line with the court requirements. The scientific community has a responsibility to support improvement of standards of scientific reasoning in the court-room.

and:

<u>Recommendation 3</u>: The methods to calculate likelihood ratios of mixtures (not considering peak area) described by Evett et al. [reference #55] and Weir et al. [reference #113] are recommended.

DNA Commission of the International Society for Forensic Genetics (ISFG): Recommendations regarding the role of forensic genetics for disaster victim identification (DVI), 2007. Prinz, Carracedo, Mayr, Morling, Parsons, Sajantila, Scheithauer, Schmitter, Schneider. Forensic Sci. Int.: Genet. 1: 3-12.

page 10:

Recommendation #11. *In DVI work, DNA statistics are best represented as likelihood ratios that permit DNA results to be combined among multiple genetic systems or with other non-DNA evidence. (…)*

ISFG: Recommendations on biostatistics in paternity testing, 2007. Gjertson, Brenner, Baur, Carracedo, Guidet, Luque, Lessig, Mayr, Pascali, Prinz, Schneider, Morling. Forensic Sci. Int.: Genet. 1: 223-231.

page 229:

The value of the scientific evidence is the likelihood ratio (PI).

Recommendations for DNA laboratories supporting Disaster Victim Identification (DVI) Operations—Australian and New Zealand consensus on ISFG recommendations, 2008. Lee, Scott, Carroll, Eckhoff, Harbison, Ientile, Goetz, Scheffer, Stringer, Turbett. Forensic Sci. Int.: Genet. 3: 54-56.

page 55:

BSAG [Biology Specialist Advisory Group] agrees with the recommendations in relation to statistical evaluations and reporting of completed identification. Most of the Forensic Laboratories in Australia and New Zealand use Likelihood ratios in both their casework and in relation to victim identification.

National recommendations of the Technical UK DNA working group on mixture interpretation for the NDNAD and for court going purposes, 2008. Gill, Brown, Fairley, Lee, Smyth, Simpson, Irwin, Dunlop, Greenhalgh, Way, Westacott, Ferguson, Ford, Clayton, Guiness. Forensic Sci. Int.: Genet. 2: 76-82.

page 77:

in response to ISFG (2006) recommendation 2

Accepted—albeit we prefer to think in terms of advising the justice system rather than the court or court-room.

and in response to ISFG (2006) recommendation 3

All laboratories in the UK consider peak height/area in their assessments. The formulae are fundamental to all mixture interpretation with or without peak height/area consideration.

Interpretation of DNA Mixtures—Australian and New Zealand consensus on principles, 2009. Stringer, Scheffer, Scott, Lee, Goetz, Ientile, Eckhoff, Turbett, Carroll, Harbison. Forensic Sci. Int.: Genet. 3: 144-145.

page 144:

regarding ISFG (2006) recommendation 1

The likelihood ratio is a common approach to mixture interpretation in Australia and New Zealand.

regarding ISFG (2006) recommendation 3

The methods to calculate likelihood ratios of mixtures (when non considering peak height or peak area) described by Curran et al. (1999) is recommended. (Note that this paper follows the same general approach as Evett et al. [reference #55] and Weir et al. [reference #113], but incorporates the effect of population substructure.)

Standards for the formulation of evaluative forensic science expert opinion, 2009. Association of Forensic Service Providers, Science & Justice 49(3): 161-164.

page 161:

The expert will base his opinion upon the four principles: balance, logic, robustness and transparency. The standards set out in this document describe the mechanism by which these principles will be applied in formulating such opinion.

Balance — The expert should address at least one pair of propositions usually one based upon the prosecution issue and one based upon an alternative (defence issue). If a reasonable alternative cannot be identified then the expert may address only the one proposition but will make it clear that he cannot evaluate the strength of the evidence.

Logic — The expert will address the probability of the evidence given the proposition and relevant background information and not the probability of the proposition given the evidence and background information.

Robustness — The expert will provide opinion that is capable of scrutiny by other experts and cross-examination. He will base his opinion upon sound knowledge of the evidence type(s) and use wherever possible verified databases. He will be satisfied that the results of the tests and examinations upon which he has based his opinion are themselves robust.

Transparency — The expert will be able to demonstrate how he came to his conclusion. He will set out in the statement or report the basis of his opinion viz.:

- *Propositions addressed.*
- *Test or examination results.*
- *The background information he has used in arriving at his conclusion.*
- *He will be able, if required, to provide the data he has used and its provenance.*

Royal Statistical Society Guidance document for Judges, Lawyers, Forensic Scientists and Expert Witnesses, 2010. C.G.G. Aitken, P. Roberts, G. Jackson, Fundamentals of Probability and Statistical Evidence in Criminal Proceedings, United Kingdom.

page 44:

Fact-finding in criminal adjudication is, generally speaking, accomplished by ordinary common sense reasoning rather than through the application of mathematical formulae, as the Court of Appeal emphatically reiterated in Adams. It should be borne in mind, however, that although most evidence adduced in criminal proceedings does not come with a pre-assigned quantified numerical value attached (e.g. what is the probability that an eyewitness identification is accurate? Or the probability that a confession is true?), much forensic science evidence (including DNA profiling) is predicated on quantified probabilities and is consequently directly amenable to Bayesian calculations. Moreover, even unquantified evidence can be assigned a subjective probability in Bayesian reasoning. Bayes Theorem is a codification of the reasoning that should be applied in the assessment of evidence. It is a statement of logic. Its application ensures evidence is assessed rationally.

Position Statement by Evett et al. (2011). Expressing evaluative opinions: A position statement, Science & Justice 51: 1-2.

page 1:

…the following issues that represent our collective position with regard to the evaluation of evidence within the context of a criminal trial:

1) The interpretation of scientific evidence invokes reasoning in the face of uncertainty. Probability theory provides the only coherent logical foundation for such reasoning.

2) To form an evaluative opinion from a set of observations, it is necessary for the forensic scientist to consider those observations in the light of propositions that represent the positions of the different participants in the legal process. In a criminal trial, the propositions will represent the positions of prosecution and defence, respectively.

3) It is necessary for the scientist to consider the probability of the observations given each of the stated propositions. Not only is it not appropriate for the scientist to consider the probability of the proposition given the observations, there is a danger that in doing so the jury will be misled.

4) The ratio of the probability of the observations given the prosecution proposition to the probability of the observations given the defence proposition, which is known as the likelihood ratio, provides the most appropriate foundation for assisting the court in establishing the weight that should be assigned to those observations.

ISFG: Recommendations regarding the use of non-human (animal) DNA in forensic genetic investigations, 2011. Linacre, Gusmão, Hecht, Hellmann, Mayr, Parson, Prinz, Schneider, Morling. Forensic Sci. Int.: Genet. 5**:** 501-505.

Page 504:

Recommendation #12*: A comprehensive casefile should be maintained. A likelihood ratio approach is the recommended way to evaluate the weight of the evidence, considering more than one proposition.*

DNA Commission of the International Society of Forensic Genetics: Recommendations on the evaluation of STR typing results that may include drop-out and/or drop-in using probabilistic methods, 2012. Gill, Gusmão, Haned, Mayr, Morling, Parson, Prieto, Prinz, Schneider, Schneider, Weir. Forensic Sci. Int.: Genet. 6: 679-688.

page 679:

The present recommendations are intended to guide scientists and laboratories that wish to use probabilistic reasoning to interpret DNA profiles where drop-out and/or drop-in is considered. The methods used can be undertaken with the likelihood ratio (LR) principle that was previously recommended for crime case work by the DNA Commission of the International Society of Forensic Genetics (ISFG) [reference #243] and for paternity/relationship testing by the Paternity Testing Commission of the ISFG [reference #185].

DNA Commission of the International Society for Forensic Genetics: Revised and extended guidelines for mitochondrial DNA typing, 2014. Parson, Gusmão, Hares, Irwin, Mayr, Morling, Pokorak, Prinz, Salas, Schneider, Parsons. Forensic Sci. Int.: Genet. 13: 134-142.

page 140:

Likelihood ratios for mtDNA then are normally calculated by 1/(match probability).

ENFSI Guideline for Evaluative Reporting in Forensic Science, 2015.

page 6, section 2.4:

Evaluation will follow the principles outlined in Guidance note 1 (refer to paragraph 4.0). It is based on the assignment of a likelihood ratio. Reporting practice should conform to these logical principles. This framework for evaluative reporting applies to all forensic science disciplines. The likelihood ratio measures the strength of support the findings provide to discriminate between propositions of interest. It is scientifically accepted, providing a logically defensible way to deal with inferential reasoning. Other methods (e.g., chemometrical methods) have a place in forensic science, to help answer other questions at different points of the forensic process (e.g., validation of analytical methods, classification/discrimination of substances for investigative or technical reporting). Equally, other methods (e.g., Student’s t-test) may contribute to evaluative reports, but they should be used only to characterize the findings and not to assess their strength. Forensic findings as such need to be distinguished from their evaluation in the context of the case. For the latter evaluative part only a likelihood ratio based approach is considered.

Royal Statistical Society Guidance document for Judges, Lawyers, Forensic Scientists and Expert Witnesses, 2015. Jackson, Aitken, Roberts. Case assessment and interpretation of expert evidence, United Kingdom.

pages 27-28, section 2.8:

For many of the issues addressed by expert evidence, forensic scientists are not in a position to assign appropriate, informed or realistic prior probabilities for material facts in issue; nor is it their role to do so. Prior probabilities are typically informed by inferential conclusions that can appropriately be made only by fact-finders in criminal adjudication. It is not the expert’s role to pre-empt or displace jury reasoning on these issues (and any institutional pressures that they may experience in this direction should be resisted by conscientious forensic scientists.)

What an expert should be in a position to offer is the assessment of a likelihood ratio (LR) for the evidence. The LR is the ratio of two probabilities, conditioned on mutually exclusive (but not necessarily exhaustive) propositions. In a forensic context, the LR can be explained generically as the ratio of: (1) the probability of the forensic scientist’s observations if the postulated fact in issue were true; to (2) the probability of the same observations on some alternative hypothesis (e.g. that the fact in issue is false). The expert presenting a likelihood ratio makes no assumption either way about the truth or falsity of the fact in issue, and therefore cannot be criticised for deliberately or *inadvertently usurping any of the jury’s responsibility for fact-finding. (Likelihood ratios were also explained in* Practitioner Guide *No 1, and employed in the evaluation of DNA profiling evidence in* Guide *No 2 in this series.)*

Morrison et al. (2017) in response to the PCAST Report. Morrison, Kaye, Balding, Taylor, Dawid, Aitken, Gittelson, Zadora, Robertson, Willis, Pope, Neil, Martire, Hepler, Gill, Jamieson, de Zoete, Ostrum, Sci. Int. 272: e7-e9.

pages e7-e8:

A more appropriate procedure would not include a “match”/“non-match” stage, would not use a threshold, and would instead directly assess two probabilities based on the continuously-valued data: (1) The probability of obtaining the measured properties of the questioned-source specimen had it come from the known source; versus (2) the probability of obtaining the measured properties of the questioned-source specimen had it come not from the known source but from some other source in the relevant population. The former is the numerator and the latter is the denominator of a likelihood ratio. There is a substantial body of literature describing and validating statistical procedures which work directly with continuously-valued data. Such statistical procedures would a priori be expected to have higher degrees of validity…

Meuwly, Ramos and Haraksim (2017). A guideline for the validation of likelihood ratio methods used for forensic evidence evaluation, Forensic Sci. Int. 276: 142-153.

page 142:

This Guideline aims at providing assistance to the forensic practitioners in determining the scope of validity and applicability of the LR methods developed and to validate the LR’s produced as forensic evidence in practice.

page 143:

Forensic research makes progress in the field of evaluation of forensic evidence. Currently, a uniform and logical inference model is used for evaluating and reporting forensic evidence [reference #122]. It uses a likelihood ratio (LR) approach based on the Bayes inference model (Theorem of conditional probabilities).

NIFS An Introductory Guide to Evaluative Reporting, 2017. National Institute of Forensic Science Australia New Zealand. 605. K. Ballantyne, J. Bunford, B. Found, D. Neville, D. Taylor, G. Wevers, D. Catoggio, National Institute of Forensic Science Australia New Zealand.

page 3:

Evaluation—The consideration of all observations in light of propositions, relevant information, limits of the testing procedure used, knowledge and experience. This may involve the assignment of a numerical value for the probability of the findings given the competing propositions or may be non-numerical and instead a statement of relative support for one proposition over the other.

page 6:

The fundamental principles of evaluative reporting or interpretation are that (i) the crime must be considered to have occurred within a framework of circumstances, (ii) that the findings must be considered in light of at least two competing propositions that will be guided by the case circumstances and (iii) that the role of the expert is to comment on the probability of their findings, given these propositions and not on the propositions themselves. It is this last principle that allows the fact-finders to combine aspects of evidence they hear during the course of the trial with their judgement in their deliberations. This framework of evidence evaluation is commonly referred to as evaluative reporting, but may also be referred to as the likelihood ratio approach, logical thinking or Bayesian inference.

Those that undertake evaluative reporting find that they are able to provide informative opinions for findings that have traditionally been considered 'inconclusive' and in ways that can be standardised between analysts within, and between, organisations and forensic disciplines.

page 7:

In evaluative reporting, probabilities are used to express the degree of certainty (and inherently the degree of uncertainty) in observing the findings in light of each proposition. (…) The probabilities assigned may be based upon empirically derived data, the results of ad hoc experimentation, practitioners experience and/or personal knowledge, with the origin of and basis for the probabilities disclosed to the Courts.

and

You will commonly hear the evidential weight provided for the findings that has been evaluated in an evaluative framework expressed as a likelihood ratio (LR). The likelihood ratio is a scale (either verbal or numerical) of support for one proposition over another.

Using evaluative reporting, a neutral result occurs when the probability of the findings is the same given both propositions (a likelihood ratio of 1). It is important to note that neutral is not the same as inconclusive—an LR of 1 simply means that the probabilities are equal. (…) If the probability of the findings favours the prosecution, the likelihood ratio will be greater than one. Conversely, if the probability of the findings favours the defence propositions, the likelihood ratio will be less than one.

page 8:

The key to evaluative reporting is the consideration of the probability of the findings given two competing propositions. Assignment and reporting of a likelihood ratio is the most common usage of this framework at present.

Inns of Court College of Advocacy and the RSS on statistical evidence and probabilistic reasoning quotes the Law Commission. ICCA/RSS guide: Statistics and probability for advocates. https://icca.ac.uk/expert-evidence or http://www.rss.org.uk/RSS/Influencing_Change/Statistics_and_the_law/Advocates_guide/RSS/Influencing_Change/Current_projects_sub/Advocates_guide.aspx?hkey=883603a7-fc93-4921-a2cc-36ac14e1cf82.

page 66:

The Law Commission's 2011 report, Expert Evidence in Criminal Proceedings in England and Wales*, recommended an expansion of the approach of two competing propositions to more forms of evidence. They recommended:*

where an expert witness is called by a party to give a reasoned opinion on the likelihood of an item of evidence under a proposition advanced by that party, the expert's report must also include, where feasible, a reasoned opinion on the likelihood of the item of evidence under one or more alternative propositions (including any proposition advanced by the opposing party)—*Law Commission, Expert Evidence in Criminal Proceedings in England and Wales (Law Com No. 325, 2011) para 7.21 (2)(c)*

They argued for this on the basis that all expert witnesses have an overriding duty to provide impartial evidence. They noted that it may not always be feasible to provide such an alternative.

Key Quotes from Academic Publications

This section presents a selection of key quotes from academic publications demonstrating a move towards a likelihood ratio (LR) approach for the evaluation of evidence in forensic science.

Poincaré, Appell, Darboux (1908). Rapport de MM. les experts Darboux, Appell et Poincaré. In: Affaire Dreyfus. La Révision du Procès de Rennes, Enquête de la Chambre Criminelle de la Cour de Cassation (5 mars 1904 – 19 novembre 1904), Tome Troisième, Ligue française pour la défense des droits de l'homme et du citoyen, Paris: pp. 499-600.

page 504:

Dans l'impossibilité de connaître la probabilité a priori*, nous ne pourrons pas dire : telle coïncidence prouve que le rapport de la probabilité de la forgerie à la probabilité inverse a telle valeur; nous pourrons dire seulement, par la constatation de cette coïncidence: ce rapport devient tant de fois plus grand qu'avant la constatation.*

Translation by S. Gittelson:

If it is impossible to know the a priori *probability, we cannot say: such a coincidence proves that the ratio of the probability of the forgery to its inverse probability has such a value; we can only say that, after observing the coincidence, this ratio becomes X times greater than before the observation.*

Finkelstein and Fairley (1970). A Bayesian approach to identification evidence, Harvard Law Review 83(3): 489-517.

pages 510-511:

By itself, a decision that defendant's hair is "similar" to the incriminating hair, by the artificial standard selected, is without probative significance. The admission into evidence of such a finding may be fatally prejudicial unless it is also shown that similar hairs are not common in the *population. Nor can it be said that a finding of dissimilarity should exculpate an accused. A hair which may be quite rare for the accused, and in this sense unlikely to have come from him, may be still more unlikely to have come from someone else. Yet if a preliminary test of similarity has been adopted, the hypothesis that the hair is his would be rejected. By combining P(H|G) and P(H|NG) into a single formula, Bayes' theorem takes both factors into simultaneous account.*

where *H* = hair, *G* = guilty, and *NG* = not guilty

Lindley (1977). Probability and the law, Journal of the Royal Statistical Society, Series D (The Statistician) 26(3): 203-220.

page 207:

(…) the technicality we need is Bayes theorem for it is this result that tells us how to update our uncertainty upon the receipt of additional evidence.

page 208:

Two important deductions follow from this result.

First, evidence should be presented to the jury in the form of statements about E, the evidence, not about G, the guilt, because it is these statements that the normative juror requires in order to update his uncertainty. Evidence is the business of the witness, guilt that of the juror. (…) We [Evett and I] argue that the scientist's task is to say what the evidence means on the supposition of guilt, and on that of innocence. But the result is true generally and not just for forensic evidence.

pages 210-211 :

(…) the calculations once done reveal three desirable qualities possessed by the normative method. Firstly, (…) there is a substantial improvement in communication from one individual to another. (…) Secondly all assumptions made have to be displayed in order to verify the calculations. (…) The third advantage possessed by the coherent method is precisely its coherence. It is the only *way in which pieces of evidence can be combined (…). Furthermore the method of combining is essentially simple, for only the rules of probability are needed. (…) The role of the human being in the legal process is therefore clear. It is he who must express his views probabilistically.*

Evett (1983). What is the probability that this blood came from that person? A meaningful question? Journal of the Forensic Science Society 23: 35-39.

page 39:

In answer to the question "What is the probability that this blood came from that person (the suspect)?" the scientist has to recognise that the suggestion that the suspect was out of the country at the time of the offence is relevant. The investigator is best placed to assess the value of this information and the scientist should confine himself to answering questions of the type "What is the probability of the blood evidence if the suspect did commit the crime?" and "What is the probability of the blood evidence if the suspect did not commit the crime?" The ratio of the two answers is crucial.

Evett (1984). A quantitative theory for interpreting transfer evidence in criminal cases, Journal of the Royal Statistical Society, Series C (Applied Statistics) 33(1): 25-32.

page 28:

The scientist's role is characterized by the likelihood ratio and questions of the type "what are the probabilities of the evidence *under the alternative hypotheses C and $\bar{C}$?"*

Stoney (1984). Evaluation of associative evidence: Choosing the relevant question, Journal of the Forensic Science Society 24: 473-482.

page 481:

To evaluate the associative evidence we ask Question 4: Given the Crime Object, what is the probability that we would encounter a corresponding object? Following this fundamental question the application of the likelihood ratio should be considered.

Evett (1986). A Bayesian approach to the problem of interpreting glass evidence in forensic science casework, Journal of the Forensic Science Society 26: 3-18.

page 7:

The Bayesian argument [reference #23] shows that the scientist's evidence F should be summarised by the likelihood ratio

$$p(F|C,I)/p(F|\bar{C},I)$$

that is, the ratio of the probabilities of F given the alternatives C and $\bar{C}$.

Evett, Cage and Aitken (1987). Evaluation of the likelihood ratio for fibre transfer evidence in criminal cases, Journal of the Royal Statistical Society, Series C (Applied Statistics) 36: 174-180.

page 176:

The problem that we address here is that of evaluating $p(Exy|CI)/p(Exy|\bar{C}I)$, the likelihood ratio (LR), though in the overall context of the investigation or trial, the prior odds are of crucial importance.

Evett (1987). Bayesian inference and forensic science: Problems and perspectives, Journal of the Royal Statistical Society, Series D (The Statistician) 36(2/3): 99-105.

page 99:

I shall concentrate on the problem of evaluating forensic science evidence against two narrower alternatives: C, the event that the suspect was at the crime scene and $\bar{C}$, the event that the suspect was not at the crime scene. (…)

The great advantage of Bayesian inference is that it enables us to identify and, in principle, to answer the most appropriate range of questions which the scientist should address to be of greatest assistance to the investigator or to the court. Bayes Theorem shows us that, while the investigator or court is concerned with questions of the type: "what is the probability that the suspect was at the crime scene?", the scientist, through the likelihood ratio, should address *questions of the type “what is the probability of the* evidence *given that the suspect was not at the crime scene?”.*

Evett and Buckleton (1989). Some aspects of the Bayesian approach to evidence evaluation, Journal of the Forensic Science Society 29: 317-324.

page 319:

The Bayesian approach directs the scientist, in the current context, to consider two questions: “What is the probability of finding this evidence if the suspect were the person who stabbed the victim?” and “What is the probability of finding this evidence if the suspect were a person selected at random?” The ratio of these two probabilities is central to the Bayesian argument. If it is greater than one then the evidence supports C; the larger it is, the greater the support. Conversely, if it is less than one then the evidence supports $\bar{C}$. (…)

The important factor is the ratio of these two probabilities---the likelihood ratio (…).

page 323:

In addition the Bayesian argument offers a coherent way of both interpreting the evidence and presenting the results. (…)

Forensic science would profit from a scale for evidential value. It is our view that the likelihood ratio presents such a scale and the “stain-at-the-scene case” provides a sound standard to underpin it. Other writers have advocated the likelihood ratio as the measure of evidential value, in particular Aitken [reference #36] and Good [reference #33].

Good (1991). Weight of evidence and the Bayesian likelihood ratio. In: C.G.G. Aitken, D.A. Stoney (Eds.), The Use of Statistics in Forensic Science, Ellis Horwood, Chichester: pp. 85-106.

pages 86-87:

We wish to express, in terms of probability, the weight of evidence in favour of guilt G provided by the evidence E given the background information I *all along. (…) Denote this weight of evidence by W(G:E|I), where the colon is read* provided by *and the vertical stroke by* given*. (…) W(G:E|I) can depend only on the probability of E given that the man is guilty and on the probability given that he is innocent (…). To state this condition more precisely, and in symbols, we assume that W(G:E|I) depends only on P(E|G&I) and P(E|$\bar{G}$&I). (…) It seems to us to be no more than common sense, (…). At any rate, based on this piece of common sense, it can be proved, as a theorem, that W(G:E|I) depends only on the* ratio *P(E|G&I)/P(E|$\bar{G}$&I). Various proofs of this simple important theorem, and allied theorems, have been given (Good 1968, 1984, 1989a, b, c).*

page 97:

Good (1968), and more lucidly in (1984), using a simpler approach than in 1960, showed that some fairly compelling desiderata for W(H:E|G), the weight of evidence in favour of H provided by *E given G all along, leads necessarily to the explicatum as the logarithm of a Bayes’ factor. Simpler arguments were given by Good (1989a, b) and the method of the latter paper is used in our Appendix. Card & Good (1974) and Good & Card (1971) used the concept in relation to medical diagnosis, and Spiegelhalter & Knill-Jones (1984) say ‘We argue that the flexible use of “weights of evidence” overcomes many of the previous criticisms of statistical systems while retaining a valid probabilistic output’. Spiegelhalter (1983) mentioned that physicians find the concept appealing. Magistrates should do so* a fortiori *because they so often have just two hypotheses to consider. It seems that jurymen, magistrates, and physicians make implicit judgements of the probabilities of* *guilt and disease states. These must again involve implicit judgements of Bayes’ factors or weights of evidence and must also take initial probabilities into account.*

Lempert (1991). Some caveats concerning DNA as criminal identification evidence: with thanks to the Reverend Bayes, Cardozo Law Review 13: 303-341.

page 320:

Turning now to the likelihood ratio, we see that the probative value of DNA evidence depends on the ratio of the probability that we would find the DNA evidence if the defendant were the source of the DNA, to the probability that we would find that same evidence if the defendant were not the source.

Stoney, D.A. (1991). Transfer evidence. In: C.G.G. Aitken, D.A. Stoney (Eds.), The Use of Statistics in Forensic Science, Ellis Horwood, Chichester: 107-138.

page 119:

The application of Bayesian methods has been well argued in this collective volume and elsewhere [references #41, 6, 11, 28, 35, 39, 34].

Evett, Buffery, Willott and Stoney (1991). A guide to interpreting single locus profiles of DNA mixtures in forensic cases, Journal of the Forensic Science Society 31(1): 41-47.

pages 42-43:

There are two possible alternative explanations for the evidence:

C: The crime samples came from suspect X and one other man

$\bar{C}$: The crime sample came from two other men.

It is necessary to evaluate the probability of the evidence found in the crime sample, given each of these alternatives, as follows. (…)

The evidential strength in relation to C is measured by the ratio of the two probabilities---the likelihood ratio [reference #23].

Evett (1992). Evaluating DNA profiles in a case where the defence is “It was my brother”, Journal of the Forensic Science Society 32: 5-14.

pages 5-6:

The probative value of this evidence is, in most cases, a function of the relative frequency with which that blood type occurs in the population. Whereas this assertion is intuitively accepted apparently universally in courts of law, the logical foundation of that relationship is often misunderstood. Clarification can be achieved by adopting a Bayesian view, along the following lines.

Within the adversary system there are two competing explanations for the evidence.

C: the suspect left the crime stain

$\bar{C}$: someone else left the crime stain

It is necessary to evaluate the probability of the evidence given each of these alternatives. In the present context, as has been explained elsewhere [reference #23], the strength of the evidence is given by the likelihood ratio.

Robertson and Vignaux (1992). Unhelpful evidence in paternity cases, New Zealand Law Journal 9: 315-317.

Bayes Rule tells us that we then take those prior odds and multiply them by the likelihood ratio of the blood/DNA evidence in order to arrive at the posterior odds in favour of the defendant's paternity. The Court then has to consider whether those odds meet the required standard of proof. Thus the expert should say 'however likely you think it is that the defendant is the father on the basis of the other evidence, my evidence multiplies the odds X times'.

Evett (1993). Criminalistics: the future of expertise, Journal of the Forensic Science Society 33(3): 173-178.

page 178:

(…) if we are to advance as scientists within a scientific discipline, then we ought to agree on some basic issues such as the class of questions which we can *address and those which we* cannot *address. In general, it is just not possible on scientific evidence alone to answer a question of the type "what is the probability that this man left that blood stain?". But it is, in general, possible to answer questions of the type "what is the probability of the evidence if the man left the blood stain?" and "what is the probability of the evidence if someone else left the blood stain?" It is the ratio of answers to these two questions which determines the strength of the evidence.*

Evett (1995). Avoiding the transposed conditional, Science & Justice 35: 127-131.

page 128:

For the interpretation of forensic transfer evidence there is considerable support for the Bayesian view which demonstrates that it is necessary to consider the probability of the evidence given whatever alternative propositions or hypotheses which are relevant to the deliberation of the court [reference #52]. If there are two alternatives, then the ratio of the two probabilities---the likelihood ratio---provides the means for placing the scientific evidence in the context of the other evidence in the following way. (…)

Robertson and Vignaux (1995). DNA evidence: wrong answers or wrong questions?, In: B.S. Weir (Ed.), Human Identification: The Use of DNA Markers, Kluwer Academic Publishers, Dordrecht: pp. 145-152.

page 145:

The question the court wishes the scientist to answer is the post-data question: 'how much does the evidence from the mark at the scene increase the probability that it was the accused who left it?' This is done by comparing the probability of the evidence (E) supposing that the accused left the mark (H1) with the probability of the evidence supposing an alternative hypothesis, usually the defense case (H2). This will enable the court to assess the value of the evidence --- in other words, to determine how much it should change its belief in the prosecution case based on other evidence. There can be no other rational purpose for giving the evidence.

page 151:

Forensic scientific evidence should be given by comparing the probabilities of obtaining the evidence under each of two relevant, specific, and positive hypotheses.

Dawid and Evett (1997). Using a graphical method to assist the evaluation of complicated patterns of evidence, Journal of Forensic Sciences 42(2): 226-231.

page 226:

There is now considerable support for the Bayesian approach to assessing evidence in the context of a legal adversary system [references #52, 81, 90, 49].

page 227:

For the purpose of this paper, we are concerned with the evaluation of the scientific evidence and we can separate it from the other evidence by means of Bayes' theorem (…). We are principally concerned with the first term on the right hand side: the likelihood ratio (LR).

Foreman, Smith and Evett (1997). A Bayesian approach to validating STR multiplex databases for use in forensic casework, International Journal of Legal Medicine 110: 244-250.

page 245:

Then, if the profiles match and x denotes the shared profile, the likelihood ratio (LR) representing the strength of evidence in support of the hypothesis that the suspect and offender are the same person is given by (…).

and

(…) it is common practice at the Forensic Science Service to calculate the LR under scenario (a) for the offender's racial group when known; otherwise, the minimum value across all racial groups is reported.

Evett and Weir (1998). Interpreting DNA Evidence—Statistical Genetics for Forensic Scientists, Sinauer Associates, Inc., Sunderland.

page 29:

It is not our claim that Bayesian inference is a panacea for all the problems of the legal process. However, we do maintain that it is the best available model for understanding the interpretation of scientific evidence. It provides insights that are not otherwise possible. In particular, we would argue that the preceding sections suggest three precepts for the forensic scientist:

1. **To evaluate the uncertainty of any given proposition it is necessary to consider at least one alternative proposition.**
   This observation is obviously more general than forensic science alone but it is well worth remembering. Within a legal trial there will be, at the very least, two competing views; one from the prosecution and one from the defense. In that situation the odds form of Bayes' theorem is applicable. (…)
2. **Scientific interpretation is based on questions of the kind 'What is the probability of the evidence given the proposition?'**
   This is the most important rule to emerge from the Bayesian formulation, and we discuss it a little more in the section on the transposed conditional.
3. **Scientific interpretation is conditioned not only by the competing propositions, but also by the framework of circumstances within which they are to be evaluated.**

We have demonstrated the relevance of I to the assignment of the probabilities in the likelihood ratio and we will give more examples later. It demonstrates that a scientist should make clear, either in his written report or statement or in his oral evidence, the perception of the circumstances within which the evaluation has been carried out.

Taroni, Champod and Margot (1998). Forerunners of Bayesianism in early forensic science, Jurimetrics Journal 38: 183-200.

page 183:

Recent publications reveal that the trend among researchers is to adopt a Bayesian approach to the evaluation of "trace" evidence—glass, fiber, and (increasingly) biological evidence. (…) Such a broad use of the Bayesian perspective not only follows from the recent achievements of statistical argument in forensic science, but also from the history of its earlier and effective use, at the turn of the century, in a great variety of trace evidence cases and contexts.

page 186:

Note that Bertillon's description of the probative value of anthropometry is similar to that of a Bayesian framework (and avoids the classic prosecutors' fallacy or the error of transposing the conditional). The information provided by the identification bureau is only one piece of evidence, which has to be corroborated by others. Bertillon never claimed that two people could not present the same set of measurements. According to Bertillon, the court, not the expert decides the suspect's identity. (…) Further, the expert should explain precisely how the strength of the evidence was enhanced.

page 187 (on Locard's writing):

Therefore, with regard to forensic science, the duties of the judge are clear: the judge must be able to understand forensic science, the duties of the judge are clear: the judge must be able to understand forensic technology and evaluate the strength of the results. Otherwise the judge's personal conviction would merely repeat the expert's views. Thus, Locard's description of the respective positions of the judge, the court, and expert witnesses is remarkably similar to the Bayesian framework.

page 192:

There are, however, legitimate uses for probability theory. The Dreyfus case offers a ready example: (…) Ninety years later, the likelihood ratio remains the only probabilistic method endorsed for use by expert forensic scientists.

pages 195-196:

"In 1934, he [Wilmer Souder, NIST] suggested the use of a likelihood ratio to assess the evidence provided by the examination of typewritten documents (…) Hilton proposed similar approaches once again in the field of handwriting examination"

page 200

"When a committee of scientists was appointed to evaluate the relevance of statistical data associated with scientific evidence in court in 1904, the committee recommended a perfect Bayesian framework."

Evett (1998). Towards a uniform framework for reporting opinions in forensic science casework, Science & Justice 38(3): 198-202.

page 200:

This [Bayes’ theorem] *is* the *fundamental formula of forensic science interpretation and its importance cannot be over-emphasised. The idea has been around since the early part of the century. Taroni et al. [reference #129] have recently discovered that is contributed to the argument of Poincaré and his colleagues in their report which was instrumental in the exoneration of Dreyfus. Mosteller and Wallace [reference #4] used a Bayesian approach in their analysis of the problem of the authorship of* The Federalist *papers and a major step forward in clarifying the role of Bayes’ theorem in the interpretation of transfer evidence was taken in 1970 by Finkelstein and Fairley [reference #6].*

and

The court is concerned with questions of the kind ‘what is the probability that the defendant committed the crime given the evidence?’ but Bayes theorem demonstrates that, for the scientist to assist the court in updating its probabilities he/she must address questions of the kind ‘what is the probability of the evidence *given that the defendant committed the crime?’ An understanding of the fundamental difference between these two different kinds of questions is essential if one is to claim any kind of scientific approach to the evaluation of evidence. There is no other logical approach that is available to us.*

Evett, Lambert and Buckleton (1998). A Bayesian approach to interpreting footwear marks in forensic casework, Science & Justice 38(4): 241-247.

page 243:

In other cases, the acquired features will be insufficient for the expert to reach this state of moral certainty. In such cases it is *possible to look at the individualisation process from a scientific perspective by asking the scientist to address two questions of the kind “what is the probability that the scene mark would have the observed features if it was left by the suspect’s shoe?”; and “what is the probability that the scene mark would have those features if it was left by another shoe of the same sole pattern?”. (…) it is necessary that he/she should have an idea, qualitative or quantitative, about the magnitude of the ratio of the two answers. This, of course, is the likelihood ratio and the larger its magnitude the greater is the support for the first proposition.*

Cook, Evett, Jackson, Jones and Lambert (1998). A model for case assessment and interpretation, Science & Justice 38(3): 151-156.

page 153:

Later the scientist will interpret the evidence by calculating the likelihood ratio (LR) which is central to the Bayesian formulation of interpretation.

page 154:

For any quantity of matching glass Q that is subsequently found, the scientist will calculate the LR (…).

Cook, Evett, Jackson, Jones and Lambert (1999). Case pre-assessment and review in a two-way transfer case, Science & Justice 39: 103-111.

page 104:

Two previous papers [references #115, 116] have described a formal model for case assessment and interpretation. (…) The model is founded on Bayesian principles and consideration of the likelihood ratio (LR) is a central concept.

Champod and Taroni (1999). The Bayesian approach, In: J. Robertson, C.G.G. Aitken, M. Grieve (Eds.), Forensic Examination of Fibres, Taylor and Francis, London: pp. 379-398.

page 380:

The Bayesian approach is especially useful with scientific evidence [references #52, 81, 90]. (…) The likelihood ratio measures the value of the evidence in terms of a pair of hypotheses, indicating if the given set of observations supports one hypothesis more than the other. (…) Forensic scientists should give the court an evaluation which illustrates the convincing force of the results [reference #64]. (…) Scientists are concerned solely with the likelihood ratio.

page 383:

The evidential value of the forensic examination consists in the assessment of the probabilities of the observations (x,y) under two competing hypotheses.

page 396:

For the assessment of the strength of scientific evidence (E) it is necessary to consider the probability of the evidence under two given competing explanations for its occurrence, respectively presented by the prosecutor and by the defence (H_1 and H_2). The value of the evidence is estimated using a likelihood ratio $LR = P(E|H_1)/P(E|H_2)$.

Champod (2000). Identification/Individualization: Overview and meaning of ID, In: J.H. Siegel, P.J. Saukko, G.C. Knupfer (Eds.), Encyclopedia of Forensic Science, Academic Press, San Diego: pp. 1077-1084.

page 1084:

Another scheme, the Bayesian interpretation framework, overcomes most of these difficulties, in particular by relaxing the necessity of adopting an open set framework. It provides a coherent way of assessing and presenting identification evidence. From a logical point of view, the concept of evidence is essentially relative to the case and its value is best expressed using a likelihood ratio.

Evett, Jackson, Lambert, and McCrossan (2000). The impact of the principles of evidence interpretation on the structure and content of statements, Science & Justice 40(4): 233-239.

page 235:

The Bayesian model represents the application of probability theory to reasoning under uncertainty. The model reveals the central importance of the likelihood ratio*, the formulation of which crystallises three key principles for the interpretation of forensic science evidence.*

1. *Interpretation of scientific evidence is carried out within a framework of circumstances. The interpretation depends on the structure and content of the framework.*
2. *Interpretation is only meaningful when two or more competing propositions are addressed.*
3. *The role of the forensic scientist is to consider the probability of the evidence given the propositions that are addressed.*

No matter how complex a case becomes, these principles should always be at the forefront of the scientist's mind. Adherence to the principles will serve to promote logical reasoning and clarity of thought.

Jackson (2000). The scientist and the scales of justice, Science & Justice 40(2): 81-85.

page 84:

What should be our core values, our guiding principles as a profession? (…)

Provide sustainable, robust evidence (…) Be expert (…) Be transparent (…) Act impartially (…) Add value (…)

If these constitute a reasonable set of guiding principles, a useful framework for forensic science, how do we make it happen?

I believe one very good way to achieve this is through scientists focusing on an evaluation of a likelihood ratio (LR) for the findings.

Taroni, Lambert, Fereday and Werrett (2002). Evaluation and presentation of forensic DNA evidence in European laboratories, Science & Justice 42(1): 21-28.

page 22:

Scientists need a methodology to evaluate, to expose and to interpret correctly the evidence at trial, which can produce reliable interpretations and can avoid pitfalls of intuition. Bayesian inference and likelihood ratios provide a logical framework for the interpretation and evaluation of DNA evidence in which the population frequency may be seen as just one of the many parameters to be considered in a complete perspective.

page 24:

Ninety years later, this way of expressing a conclusion, giving only the likelihood ratio, is still presented as the only one authorised for forensic scientists [reference #65].

page 26:

(…) for about ten years, the evaluation of trace evidence in specialised scientific literature has been associated with the likelihood ratio perspective. Also recent publications testify to this trend [reference #121], and some forensic science services are applying this approach to a wide range of forensic evidence.

and

For the assessment of the strength of DNA evidence (E) it is necessary to consider the probability of the evidence under two competing propositions for its occurrence, respectively presented by the prosecutor H_1 and by the defence H_2. The value of the evidence is given by a likelihood ratio, $P(E|H_1)/P(E|H_2)$.

page 27:

The Bayesian framework provides an ideal model for the evaluation of scientific evidence.

Aitken and Taroni (2004). Statistics and the Evaluation of Evidence for Forensic Scientists, 2nd ed., John Wiley & Sons Ltd, Chichester.

pages 101-102:

Notice the important point that in the evaluation of the evidence Ev it is two probabilities that are necessary: the probability of the evidence if the suspect is guilty and the probability of the evidence if the suspect is innocent. For example, it is not sufficient to consider only the probability of the evidence if the suspect is innocent and to declare that a small value of this is indicative of guilt. The probability of the evidence if the suspect is guilty has also to be considered.

Similarly, it is not sufficient to consider only the probability of the evidence if the suspect is guilty and to declare that a high value of this is indicative of guilt. The probability of the evidence if the suspect is innocent has also to be considered. An example of this is the treatment of the evidence of a bite mark in the Biggar murder in 1967-68 (Harvey et al., 1968), an early example of odontology in forensic science. In that murder a bite mark was found on the breast of the victim, a young girl, which had certain characteristic marks, indicative of the conformation of the teeth of the person who had bitten her. A 17-year-old boy was found with this conformation and became a suspect. Such evidence would help towards the calculation of $Pr(Ev|H_p)$. However, there was no information available about the incidence of this conformation among the general public. Examination was made of 342 boys of the suspect's age. This enabled an estimate—albeit an intuitive one—of $Pr(Ev|H_d)$ to be obtained and to show that the particular conformation found on the suspect was not at all common.

page 213:

The Bayesian approach provides an intellectually rigorous approach to the analysis of uncertainty in the evaluation of evidence. It enables the implications of assumptions to be considered thoroughly. It enables questions of uncertainty to be answered in a coherent probabilistic manner. The cases discussed here have illustrated how various aspects of the legal process may be assisted with the Bayesian approach:

- *The likelihood ratio—illustrated here as to how the combination of more than one piece of evidence (R. v. Adams, D.J.) may be evaluated and how the interpretation of certain cases (R. v. Clark) may be aided. See also Kaye and Koehler [reference #201] for further justification of the use of the likelihood ratio to measure the probative value of evidence.*
- *Consideration of all the evidence—illustrated by the case of R. v. Adams, D.J.*
- *Definition of propositions—the evaluation of evidence depends on the propositions put forward by both the prosecution and the defence (R. v. Clark).*
- *Relevant population—this needs to be defined carefully in order that the prior odds are assessed properly. Also, for DNA profiles, the frequency of the profiles depends on the ethnic origins of the donor of the profile, and consideration has also to be given to the possible involvement of relatives.*

pages 246-247:

The odds form of Bayes' theorem presents a compelling intuitive argument for the use of the likelihood ratio as a measure of the value of the evidence. A mathematical argument exists also to justify its use. A simple proof is given in Good (1991) [chapter in reference #52] and repeated here for convenience. (…)

page 248:

Notice that the representation of the value of evidence as a likelihood ratio enables successive pieces of evidence to be evaluated sequentially in a much more intuitive and simpler way than can be done with significance probabilities

Jackson, Jones, Booth, Champod and Evett (2006). The nature of forensic science opinion—a possible framework to guide thinking and practice in investigations and in court proceedings, Science & Justice 46(1): 33-44.

page 35:

Bayes' theorem offers a practical, robust mechanism for inductive reasoning. The theorem provides a logical framework to appraise the value of new pieces of information and to update *one's uncertainty about a questioned event. It is gaining wide acceptance as a robust approach to forensic science problems and it is the basis of the CAI model [reference #115]. Of central importance in the CAI model is the concept of a* likelihood ratio *(LR).*

page 38:

The early CAI papers [references #115, 116, 148, 149] concentrated on the scientist's role as a case progresses towards court and on the evaluation of an LR for the scientific findings. (…) The role of the forensic scientist could then be defined as that of providing an LR for the scientific findings. We would suggest then that a working description of what we could call an evaluative *opinion would be:*

> *an expression of the magnitude of the LR*

page 39:

We propose three types of forensic science opinion.

Investigative *opinions*

- *explanations, or conjectures, for observations, sometimes associated with posterior probabilities for the explanations*

Preliminary evaluative *opinions*

- *expressions of the likelihoods for the findings, given the truth of individual propositions*

Fully evaluative *opinions*

- *expressions of the magnitude of the likelihood ratio.*

Buckleton, Triggs and Champod (2006). An extended likelihood ratio framework for interpreting evidence, Science & Justice 46(2): 69-78.

page 70:

The idea of assessing the weight of the evidence using a relative measure (known as the likelihood ratio), explored at the beginning of the 20th Century [reference #129], has been implemented routinely in paternity cases since 1930 [reference #2]. It is however only in the latter stages of the 20th century that it made inroads into many other fields of forensic science [references #10, 23]. It now dominates the literature as the method of choice for interpreting forensic evidence across evidence types [references #81, 90, 121, 187, 146].

Taroni, Bozza, Biedermann, Garbolino, and Aitken (2010). Data Analysis in Forensic Science: A Bayesian Decision Perspective, John Wiley & Sons Ltd, Chichester.

page 11:

Practical applications of patterns of reasoning corresponding to a Bayesian approach can be found, for example, as early as the beginning of the 20th century) [reference #129]. Bayesian ideas for inference then entered legal literature and debates more systematically only in the second half of the twentieth century. Kingston [reference #5], Finkelstein and Fairley [reference #6] and Lindley [reference #10] are some of the main reference publications from that period. Later, within the 1990s, specialized textbooks from Aiken and Stoney [reference #52], Aitken [reference #81] and Robertson and Vignaux [reference #90] appeared. During the past decade, further textbooks—along with a regular stream of research papers—focusing on Bayesian evaluations of particular categories of evidence, such as glass [reference #146] or DNA [references #218, 222] were published.

Berger, Buckleton, Champod, Evett and Jackson (2011). Evidence evaluation: A response to the court of appeal judgement in R v T, Science & Justice 51(2): 43-49.

page 44:

The phrase "likelihood ratio" and the role of Bayes' theorem in establishing a logical framework for forensic inference now appear so widely in the forensic science literature that we do not consider it necessary to explain the mathematical background.

page 49:

The likelihood ratio is a central element in a framework for evaluative opinion that is both logical and balanced.

Redmayne, Roberts, Aitken and Jackson (2011). Forensic science evidence in question, Criminal Law Review 5(347): 352-353.

page 353:

This also facilitates scrutiny and challenge by an opposing expert—which is a structural expectation of adversarial criminal proceedings, and something that courts should especially welcome in an era of proactive trial management in which judges are expected to manage and clarify expert disagreement through pre-trial processes. Last but surely not least, a probabilistic approach employing likelihood ratios is an application of logical thinking. It encourages analytical rigour and balance in the production of forensic science evidence, specifically because it requires the expert to think in terms of competing defence and prosecution explanations and to take account of all aspects of the evidence relevant to forming a scientific opinion.

Neumann, Evett, Skerrett and Mateos-Garcia (2011). Quantitative assessment of evidential weight for a fingerprint comparison I. Generalisation to the comparison of a mark with set of ten prints from a suspect, Forensic Sci. Int. 207: 101-105.

page 101:

These [the propositions] *are evaluated by the calculation of a likelihood ratio (LR) and Good [reference #3] has shown that weight of evidence is meaningfully assessed by the logarithm of the LR.*

Neumann, Evett and Skerrett (2012). Quantifying the weight of evidence from a forensic fingerprint comparison: A new paradigm, Journal of the Royal Statistical Society, Series A (Statistics in Society) 175(2): 371-415.

page 376:

Following Lindley and many others, our objective is to assign a value to the likelihood ratio LR (…).

page 394:

(…) longer term we expect an evolution towards a framework that is similar to that which underpins DNA evidence. (…) The work we describe here represents, we believe, an important contribution to that change. Already, it has formed the basis of training workshops in the UK, USA and in Europe. The response from practitioners has been cautious but predominantly favourable. (…) Ultimately, we see this kind of approach replacing the existing paradigm (…).

Steele and Balding (2014). Statistical evaluation of forensic DNA profile evidence, Annual Review of Statistics and Its Application 1: 361-384.

page 367:

Despite substantial resistance, not least from judges unfamiliar with quantitative evidence evaluation, the use of likelihoods as the primary tool for evidence evaluation has gained ground in recent years [reference #380]. In simple settings, we can form a likelihood ratio [references #55, 121]

LR = Pr(E|Hp)/Pr(E|Hd) *Equation 1.*

where E denotes the evidence and Hp and Hd represent competing hypotheses corresponding to the prosecution and defense positions, respectively.

Many difficulties may arise in putting Equation 1 into practice, and some proponents of using LRs in the legal process have understated these challenges. However, these difficulties are more easily overcome than are the problems faced by alternative methods of evidence evaluation that lack the sound conceptual basis of likelihood-based analyses [reference #90].

Taroni, Biedermann, Bozza, Garbolino and Aitken (2014). Bayesian Networks for Probabilistic Inference and Decision Analysis in Forensic Science, 2nd ed., John Wiley & Sons Ltd, Chichester.

page 87:

Note that in the evaluation of the findings Ev, two probabilities are necessary: the probability of the finding if the suspect is guilty and the probability of this finding if the suspect is innocent. For example, it is not sufficient to consider only the probability of the outcome if the suspect is innocent and to declare that a small value of this is indicative of guilt. The probability of this outcome if the suspect is guilty also needs to be considered. Similarly, it would not be sufficient to consider only the probability of the outcome if the suspect is guilty and to declare that a high value of this is indicative of guilt. Again, the probability of this outcome if the suspect is innocent has also to be considered.

page 89:

(…) the logarithm of the likelihood ratio is known as the weight of evidence*, an expression widely attributed to Good [reference #3].*

Robertson, Vignaux and Berger (2016). Interpreting Evidence: Evaluating Forensic Science in the Courtroom, 2nd ed., John Wiley & Sons Ltd, Chichester.

page 11:

(…) in the real world, evidence is something that is more or less likely to occur when what we are trying to prove is true, than when it is not. Good or strong evidence would be something that is much more likely to occur when what we are trying to prove is true, than when it is not.

For example, during a career of interviewing, a doctor might observe that a high proportion of abused children display signs of stress such as nail-biting. This will be evidence for abuse if and only if abused children are more likely to bite their nails than non-abused children. If it turned out that abused and non-abused children are equally likely to bite their nails, then this observation is *useless as evidence of abuse. If abused children are much more likely to bite their nails than non-abused, then we have strong evidence of abuse. Suppose 80% of abused children bite their nails but only 10% of other children do so. Nail-biting would then be eight times more likely in an abused child than in some non-abused child. If, on the other hand, 90% of non-abused children bite their nails, then nail-biting would be evidence pointing away from abuse.*

There are two points to notice: first, the strength (or probative value) of the evidence depends not only on how many abused children bite their nails but also on how many non-abused children do so; secondly, and most importantly, all we know at this stage is the probability of the evidence in each case. We do not know how likely it is that the child has been abused.

The probative value of any evidence can be evaluated in the same way. A scientific test result is good evidence for a particular hypothesis if it is much more likely to occur if the hypothesis is true, than if it is false.

Buckleton, Bright and Taylor (2016). Forensic DNA evidence interpretation, 2nd ed., CRC Press, Boca Raton.

page 241:

The mixed DNA profile must inform some issue of relevance to the court. This issue is often, but not always, the identity of the person who left the material from which the profile has been developed. The LR can be placed straightforwardly into a context where it can be used by the court to assess the probability of this issue given the scientific evidence. CPI does not have this direct relationship to the issue.

Bieber, Buckleton, Budowle, Butler and Coble (2016). Evaluation of forensic DNA mixture evidence: Protocol for evaluation, interpretation, and statistical calculations using the combined probability of inclusion, BMC Genetics 17(125).

page 3:

The authors recommend moves in favour of using the likelihood ratio (LR) approaches and laboratories have been embracing LR application. Use of the LR also must consider the possibility of allele drop-out; but the LR approach has more flexibility than that of the CPI to coherently incorporate the potential for allele drop-out in complex mixtures (i.e., the so-called probabilistic genotyping methods).

Curran and Weir (2016). Modern methods of DNA interpretation, Chance 29(1): 17-26.

page 21:

The likelihood ratio is very attractive because, first, it allows the expert to fulfill the role given to them by the court, namely to comment on the value of the evidence and, second, it provides a mathematically elegant way of updating one’s belief about the hypotheses through the odds form of Bayes’ Theorem:

The court wants the posterior odds: “How much more likely does this evidence make it that the accused is guilty?” Jurors have their own prior odds: “What do I believe about these hypotheses?” and the likelihood ratio provides the link between the two.

Champod, Lennard, Margot and Stoilovic (2016). Fingerprints and Other Ridge Skin Impressions, 2nd ed., CRC Press, Boca Raton.

pages 71-73:

The first key question (…) then becomes (with the c *here referring to the comparison phase):*

$Q1_c$ How probable is it to observe the features in the mark and in the submitted print in correspondence, meaning within tolerances, if these have come from the same source?

(…)

Hence, once the examiner is confident that they cannot exclude, the only question that needs to be addressed is simply:

$Q2_c$ What is the probability of observing the features in the mark (given their tolerances) if the mark originates from an unknown individual?

If the ratio is calculated between the two probabilities associated with $Q1_c$ and $Q2_c$, we obtain what is called a likelihood ratio (LR). $Q1_c$ becomes the numerator *question and $Q2_c$ becomes the* denominator *question.*

(…)

In a nutshell, the numerator is the probability of the observed features if the mark is from the POI, while the denominator is the probability of the observed features if the mark is from a different source. When viewed as a ratio, the strength of the observations is conveyed not only by the response to one or the other of the key questions, but by a balanced assessment of both. The numerator of the ratio invites the examiner to consider the within-source variations, whereas the denominator of the ratio is more focused on between-source variations. Having equal attention on both sides of the problem is the key to a fair and balanced assessment. This echoes the early call from Bertillon (1912) that the examiner should, in fact, be as focused on dissimilarities as on concordances, and not be driven by the correspondences while ignoring or explaining away differences. The LR is especially suitable for assessing the contribution of forensic findings. It applies regardless of the type of forensic evidence considered and has been put at the core of evaluative reporting in forensic science (Willis 2015) [reference #539].

Morrison (2017) in response to the NIST Lund & Iyer report. A response to: “NIST experts urge caution in use of courtroom evidence presentation method”, arXiv:1710.05878v1.

NIST experts urge caution in use of courtroom evidence presentation method” was released on October 12, 2017, and was picked up by the phys.org news service. It argues that, except in exceptional cases, the results of forensic analyses should not be reported as “likelihood ratios”. The press release, and the journal article by NIST researchers Steven P. Lund & Harri Iyer on which it is based, identifies some legitimate points of concern, but makes a strawman argument and reaches an unjustified conclusion that throws the baby out with the bathwater.

Properly understood, the likelihood ratio framework describes what is logically necessary for a forensic scientist to evaluate the strength of forensic evidence.

A Non-Exhaustive List of Publications

This section presents a non-exhaustive list of publications on the Bayesian approach, in particular the assignment of a likelihood ratio (LR), to the evaluation of evidence in forensic science. The references are orderd chronologically, and within a given year, alphabetically. They go through February 2018. Guidelines, standards, and position statements appear in **bold**.

Before 1980

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